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by Richard L. Monroe

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Sol Telecommunications Services, Inc.
2000 Corporate Ridge, Suite 810
McLean, VA 22102

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The feasibility of an EMP simulator consisting of a high-voltage pulse generator driving a small loop antenna is investigated. It is shown that such a simulator could be used to make direct time domain measurements of the shielding effectiveness of small enclosures like the S280C tactical electronics shelter using a method analogous to the frequency domain technique employed in the small loop test described in MIL-STD-285 and IEEE-299. Specifications are given for a simulator that would reproduce the waveforn, structure, and polarization of an EMP field over a 4 m^2 plane surface with a peak field of 2.7 A/m. The simulator consists of a 2 MV generator with a 0.755 pf storage capacitor and a resistance of 331 ohms driving a 0.3 m square loop formed from conductors with 1 cm radii. In operation, the loop is oriented with its plane perpendicular to the surface of the enclosure and its center 2.5 m from that surface.

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1. INTRODUCTION

A recent study[1] has suggested that small loops driven by pulse generators could be used to create transient source fields for the purpose of measuring the efficiency of small tactical shelters like the S280C (fig. 1) as shields against EMP (electromagnetic pulse) fields. This source, together with appropriate sensors at designated locations inside the enclosure, would comprise a time domain analog of the small loop test described in MIL-STD-285[2] and IEEE-299.[3] As prescribed by these standards, the loop would be located close to the shelter with its plane perpendicular to the plane of the shelter wall in order to maximize coupling to the interior. The objective of the pulsed loop would be to generate a field on a designated area of the enclosure surface that matches the structure and waveshape of the EMP so that the efficiency of that region as an EMP shield can

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[1] R. L. Monroe, A Theory of Electromagnetic Shielding with Applications to MIL-STD 285, IEEE-299, and EMP Simulation, Harry Diamond Laboratories, HDL-CR-85-052-1, (February 1985).

[2] Department of Defense, MIL-STD-285, Method of Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes (25 June 1956).

[3] IEEE, Proposed IEEE Recommended Practices for Measurement of Shielding Effectiveness of High Performance Shielding Enclosures, IEEE 299, IEEE Inc., NY (June 1969).

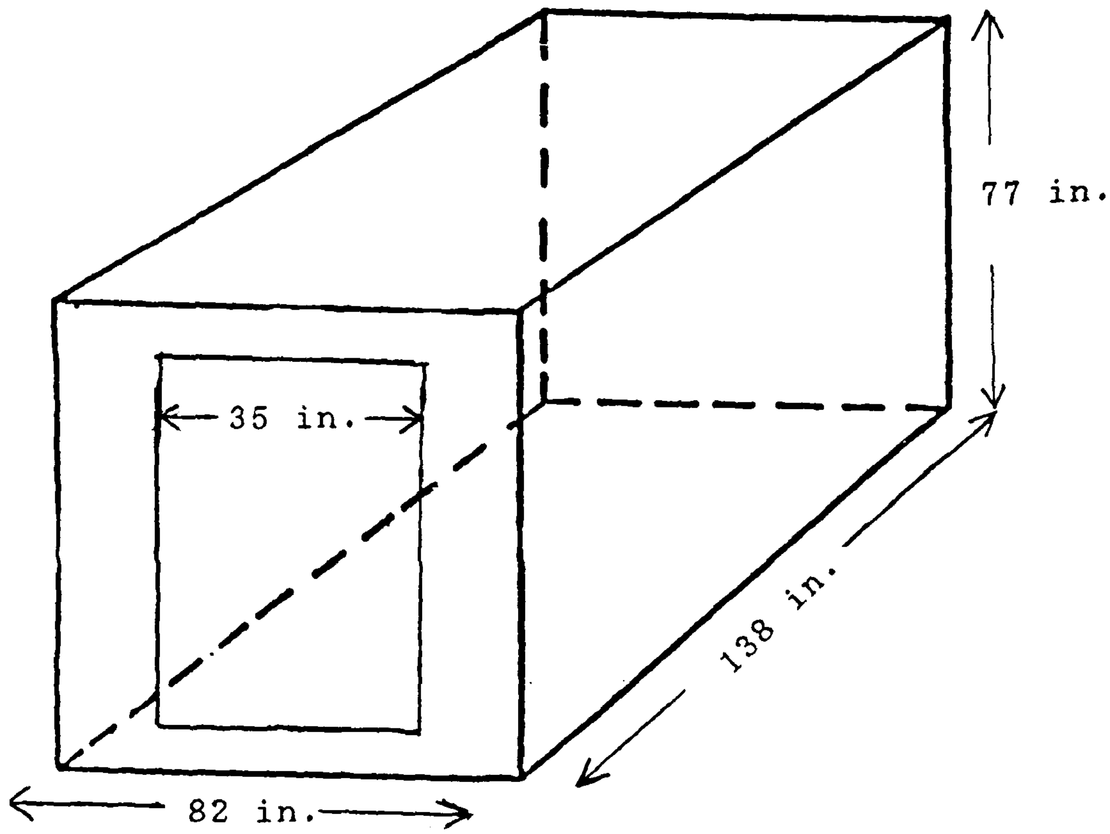

Figure 1. The S280C tactical electronics shelter.

be determined directly. With this approach, the overall efficiency of the enclosure would be determined by repeating the measurements at different locations until all surfaces exposed to the EMP are covered.

The use of a small loop as a piece-wise EMP simulator in this manner is possible because the electric and magnetic fields inside a shielded enclosure produced by any external source depend only on the tangential components of the source magnetic field on the outside surface of the enclosure[1]. That is, the internal fields are virtually independent of the source electric field. Consequently, any two sources that produce the same or nearly the same tangential magnetic fields on the outside of the enclosure will be indistinguishable from inside the enclosure, and any source that reproduces another source's tangential magnetic field on the surface of the enclosure can simulate that source as far as internal electric and magnetic fields are concerned. Thus an efficient magnetic field source like the loop can simulate an EMP over a designated region by approximating the structure and waveshape of the EMP's tangential magnetic field without any need to simulate its electric field. A comparison of the internal fields with the simulated EMP magnetic field from this source can then be taken as a measure of the effectiveness of that region as a shield against EMP fields.

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[1] R. L. Monroe, A Theory of Electromagnetic Shielding with Applications to MIL-STD 285, IEEE-299, and EMP Simulation, Harry Diamond Laboratories, HDL-CR-85-052-1, (February 1985).

The decoupling of internal electric and magnetic fields from external electric fields occurs because shielded enclosures are composed of materials belonging to the class of good conductors and are constructed in such a way that all openings (nonconducting areas in the enclosure walls) are incorporated in structures that are equivalent to waveguides beyond cutoff. These measures insure that the net electric field (incident plus reflected field) at the surface of the enclosure is very small and is determined not by the electric field of the external source but by an impedance function that characterizes the surface of the enclosure. The relationship between the impedance function and the electric and magnetic fields at the surface is expressed by impedance boundary conditions. Shielded enclosures must satisfy such conditions at all points in order to function properly. If an enclosure should fail to satisfy impedance boundary conditions because of damage or poor design, this failure will be revealed by severely degraded shielding performance.

In this note, we will investigate the feasibility of small loops as simulators of high-altitude EMP (HEMP) fields over a portion of an enclosure surface. The characteristics of the HEMP magnetic field that the simulator must reproduce are its polarization (direction), spatial variation (change in magnitude as a function of position), and waveshape (time history). Since HEMP fields incident at the surface of the earth can be approximated as uniform plane waves with both vertical and horizontal components over scale sizes corresponding to the dimensions of the S280C and with average time histories like that shown in figure 2[4], the basic function of the simulator must be to generate a spatially uniform, unipolar, transient magnetic field in any desired direction with a risetime (time to peak field) of 10 ns = 10×10^{-9} s or less. For purposes of testing the shielding properties of enclosures, it is not necessary that the simulator produce peak magnetic fields as large as the HEMP, although such a capability would be very useful for other types of tests. The basic objective here is to produce a large enough external field with the correct waveform over a sufficiently large area of the enclosure so that the internal fields can be measured.

In the following section, we will show that a small loop can indeed produce a uniform magnetic field over a significant area on a nearby plane surface and that the direction of the field can easily be varied from horizontal to vertical. This demonstration will reveal the basic tradeoff between field strength and exposure area that controls the performance of this type of simulator. Section 3 will examine circuit paarmeters for a pulse generator to drive the loop with a transient current that will produce a magnetic field with the EMP waveshape. The results of these sections will then be combined in section 4 to give specifications for a device that will simulate the HEMP magnetic field over an area of 4 m^2 with a peak field of at least 1 A/m.

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[4]Bell Laboratories, EMP Engineering and Design Principles, Whippany NJ (1975).

(a)

(b)

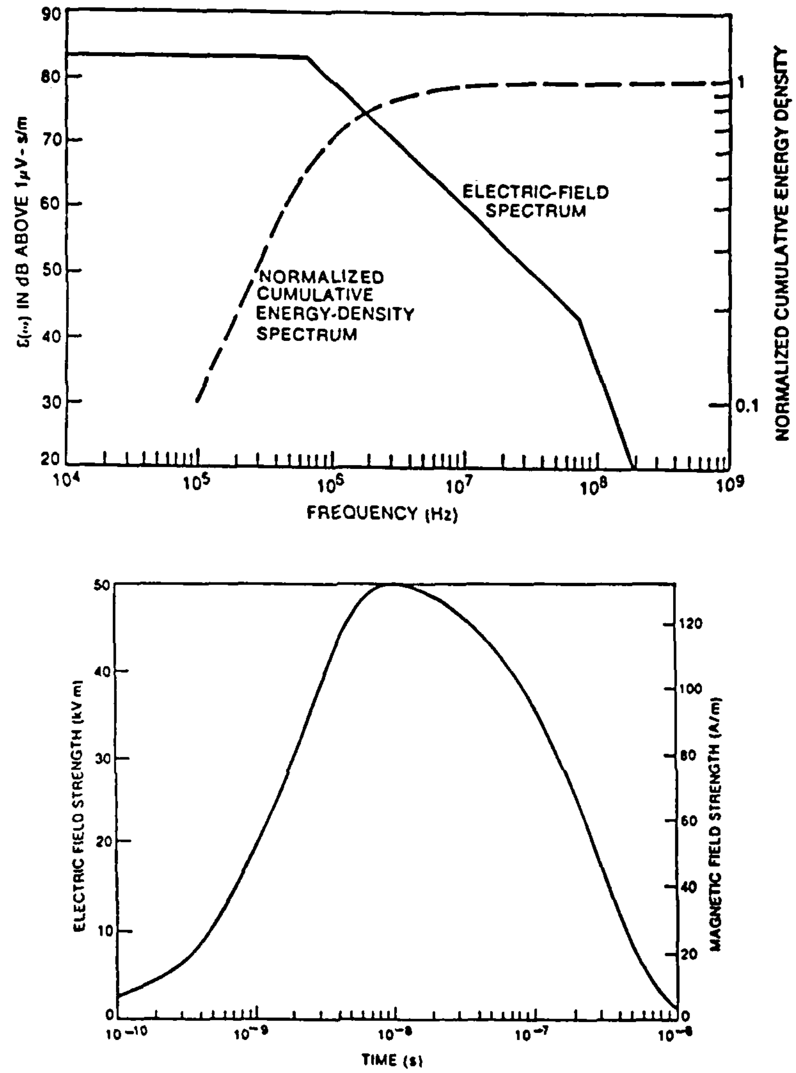

Figure 2. Average EMP field: (a) frequency domain and (b) time domain (reproduced from ref. 4).

2. MAGNETIC FIELD DISTRIBUTION OF A SMALL LOOP

A loop is considered small as a radiating structure if its enclosed area A is such that

$$A^{1/2} << \lambda = C_o/f \tag{2.1}$$

where λ is the wavelength of its transmitted field, C_o is the velocity of light, and f is the frequency of the source. When this condition is satisfied, the current distribution on the loop is uniform (independennt of position) and its fields differ little from those of a point dipole source even at locations in the extreme near field.[1] Since λ is inversely proportional to f, (2.1) can be used to estimate the maximum allowable size for any small loop over a specified range of frequencies. Thus a small loop simulator for the HEMP field shown in figure 2 will be limited by

$$A^{1/2} << 3 \times 10^8/1 \times 10^8 = 3 \text{ m} \tag{2.2}$$

since this field includes a continuous range of frequencies from 0 to 10^8 Hz. The preceding gives

$$a \cong 0.3 \text{ m} \tag{2.3}$$

as an upper limit for the size of a small square loop over the frequency range of interest. In the following, we will observe the limit imposed by (2.3) and consider only small square loops less

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[1] R. L. Monroe, A Theory of Electromagnetic Shielding with Applications to MIL-STD 285, IEEE-299, and EMP Simulation, Harry Diamond Laboratories, HDL-CR-85-052-1, (February 1985).

than or equal to 0.3 m on a side as candidates for the simulator. One could, of course, consider larger loops or loops with different shapes. However, it is believed that these would offer no advantages. In fact, larger loops would inevitably increase the inductance in the driver circuit- a result that is usually undesirable. Thus the natural tendency is to consider smaller rather than larger loops. As far as shape is concerned, it appears to have little effect on the performance.

For design purposes, the small square loop offers the additional advantage that its near-field distribution is relatively easy to compute using expressions developed in Monroe[1] (equ. (5.39)). These expressions are referred to the rectangular/cylindrical coordinate shown in figure 3 where the plane of the loop lies in the y,z plane with its center C(0,0,d) on the z axis a distance d from the origin. With this arrangement, the field distribution in the x,y plane due to a uniform harmonic current with amplitude I on the loop can be computed by setting z = 0 in (5.39) and then specifying the frequency f, the dimensions of the loop a = b, its distance from the x,y plane d = H, and the coordinates of the point in the x,y plane where the field is to be computed. Figure 4 is a plot of the magnitude H(0,0) of the magnetic field at the origin versus f computed from

[1] R. L. Monroe, A Theory of Electromagnetic Shielding with Applications to MIL-STD 285, IEEE-299, and EMP Simulation, Harry Diamond Laboratories, HDL-CR-85-052-1, (February 1985).

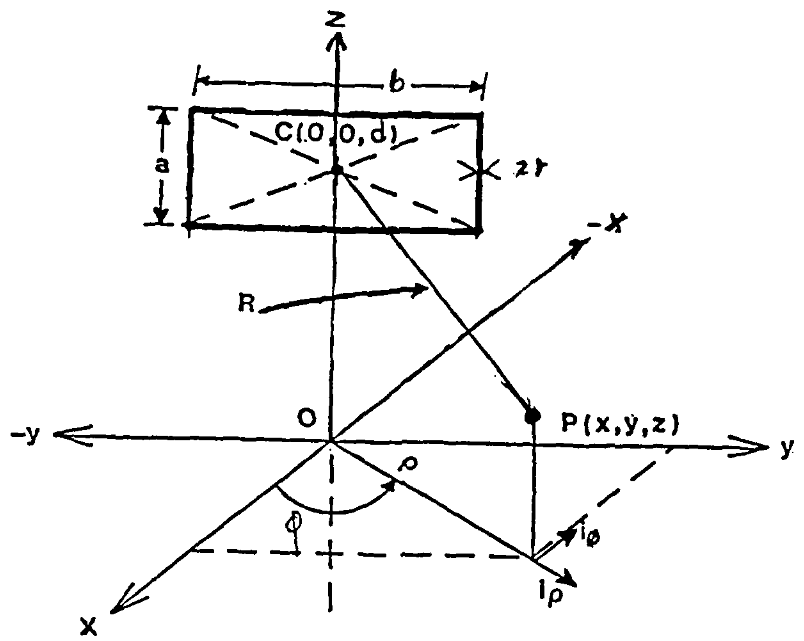

Figure 3. A rectangular loop composed of a conductor with radius r and linear dimensions a and b lying in the y,z plane of a rectangular/cylindrical coordinate system.

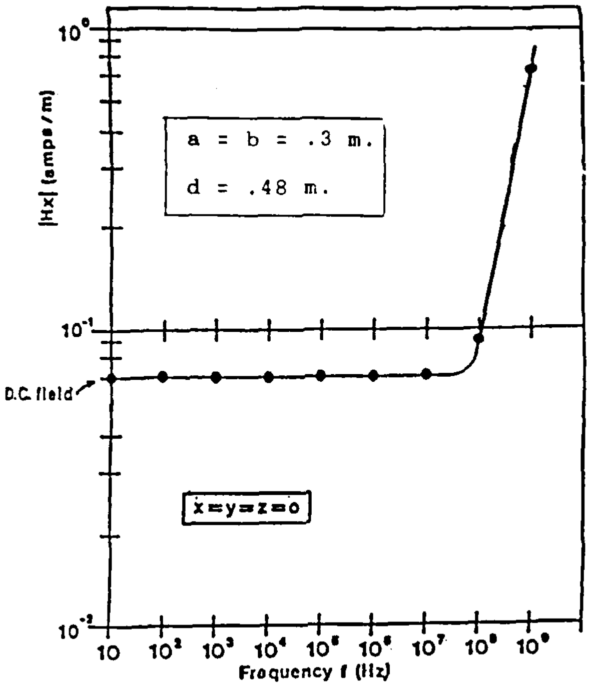

Figure 4. Magnetic field versus frequency at the point x=y=z=0 due to a uniform harmonic current of unit magnitude on a loop antenna with dimensions a = b = .3 m lying in the y,z plane with its center located a distance d = .48 m from the x,y plane.

equation (5.39) for a harmonic current of unit amplitude ($I = 1$ A)where $a = b = 0.3$ m and $d = 0.48$ m. This plot illustrates another useful property of the small loop, namely, a flat response over a very wide range of frequencies which in this case includes the EMP frequencies 0 to 1×10^8 Hz. This means that when the harmonic current source is replaced on the loop by a transient source with a bandwidth of 100 MHz or less the waveshape of the magnetic field in the x,y plane will be an image of the current on the loop. With this loop, one can adjust the parameters of a driver circuit to produce a transient current with the correct EMP waveform and be assured that the current will generate a magnetic field in the x,y plane with the same waveform. We will take advantage of this fact in the following section to specify a pulse generator for the simulator.

The flat response of the loop also means that we can compute the magnetic field distribution throughout the entire x,y plane using (5.39) at a single frequency, say 1 MHz, and that distribution will be valid for all frequencies in the range 0 to 100 MHz. This has been done to obtain figures 5 through 9, where the continuous lines forming three nested rectangles are scale drawings of the side, front, and door of the S280C shelter. The line segments originating on a rectangular grid of points spaced 0.2 m apart represent, by their length and direction, the magnitude and direction of the magnetic field in the x,y plane at those points. In this representation, the magnitude of the field at each point is normalized to the field H(0,0) at the origin (0,0) which is assigned a length equal to the grid spacing 0.2 m. Since H(0,0) is always the maximum field in

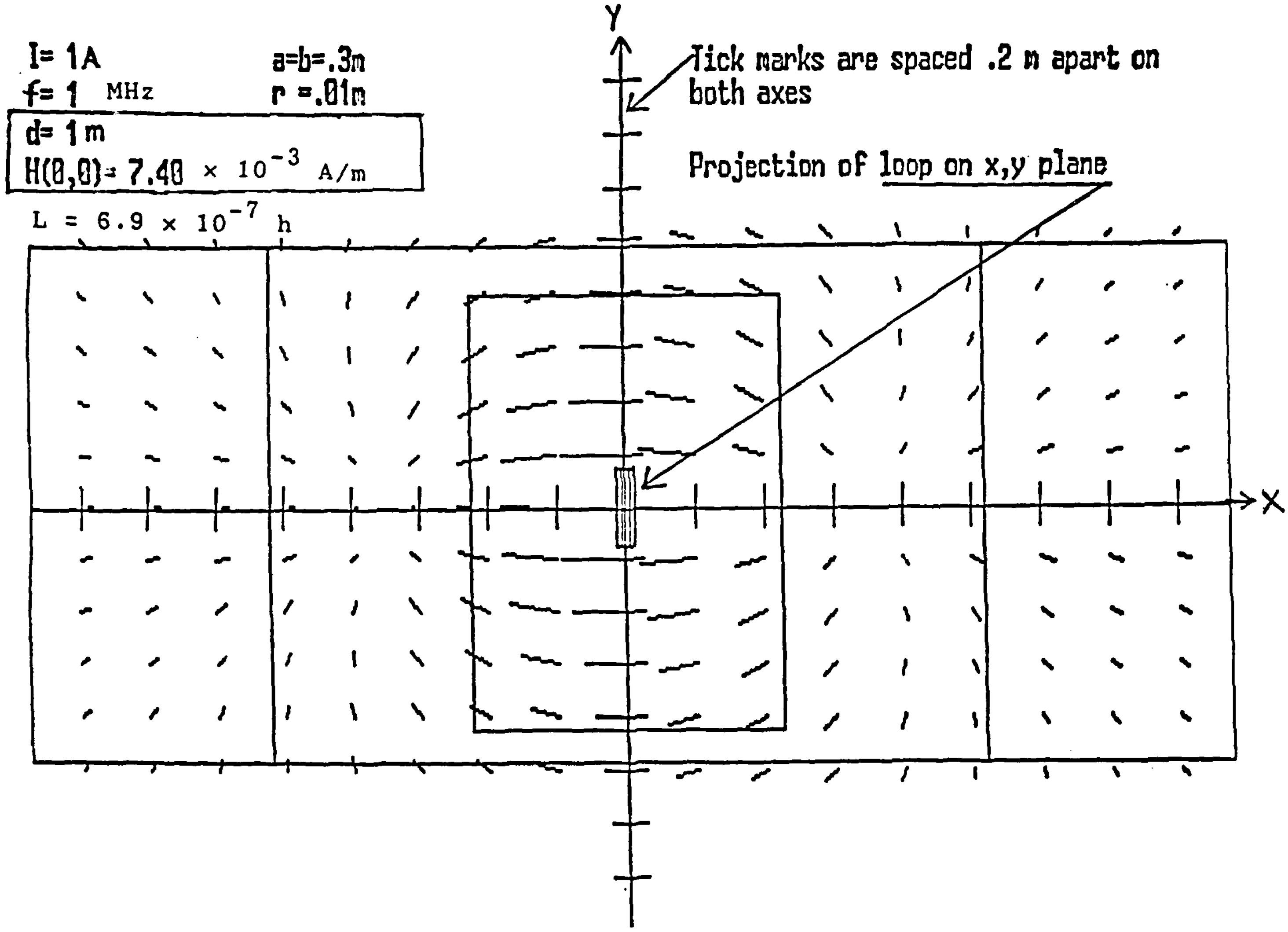

Figure 5. Magnetic field distribution in the x,y plane due to a uniform harmonic current of unit magnitude on a loop antenna with a = b = .3 m lying in the y,z plane with its center located a distance d = 1 m from the x,y plane.

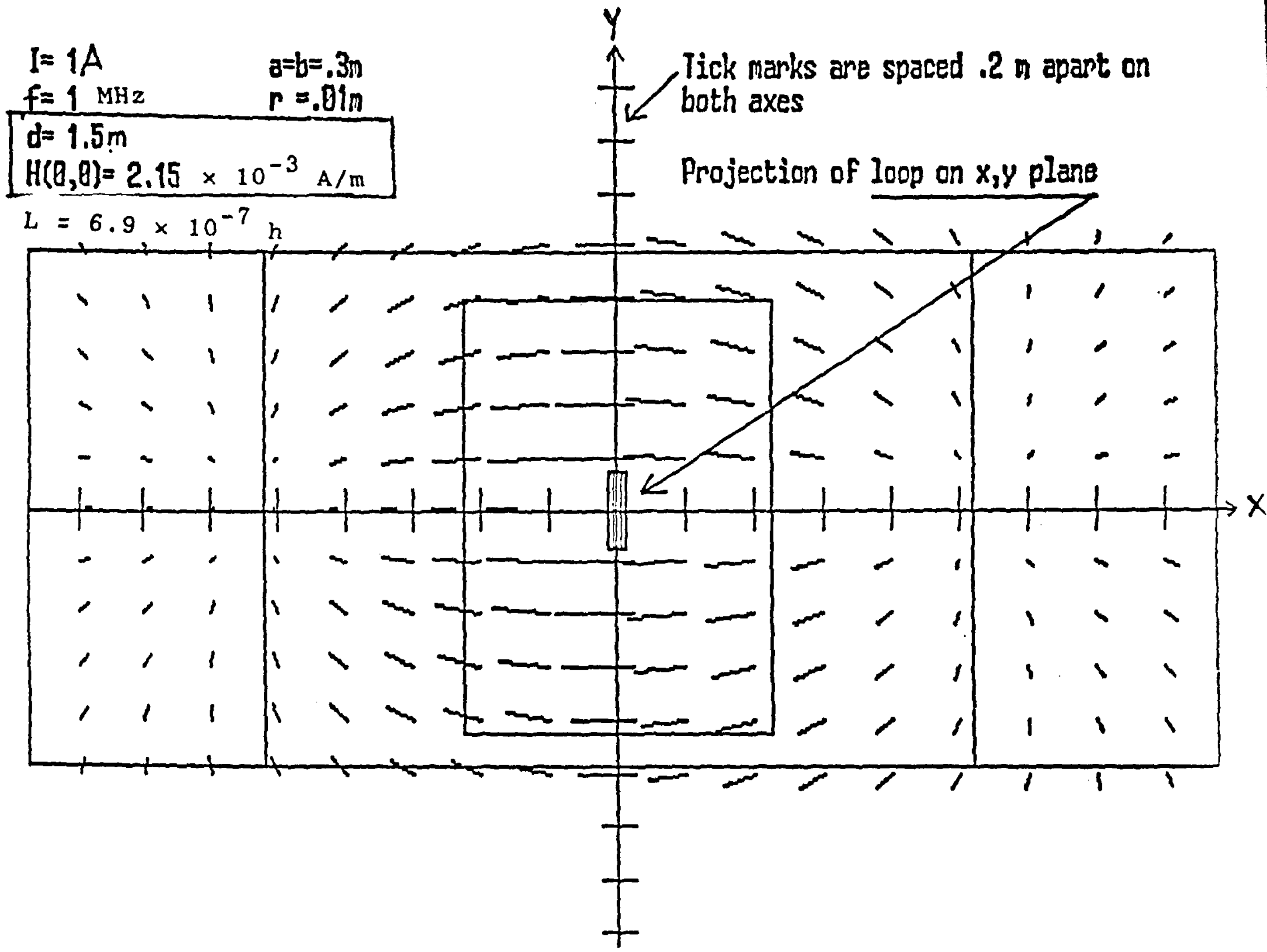

Figure 6. Magnetic field distribution in the x,y plane due to a uniform harmonic current of unit magnitude on a loop antenna with a = b = .3 m lying in the y,z plane with its center located a distance d = 1.5 m from the x,y plane.

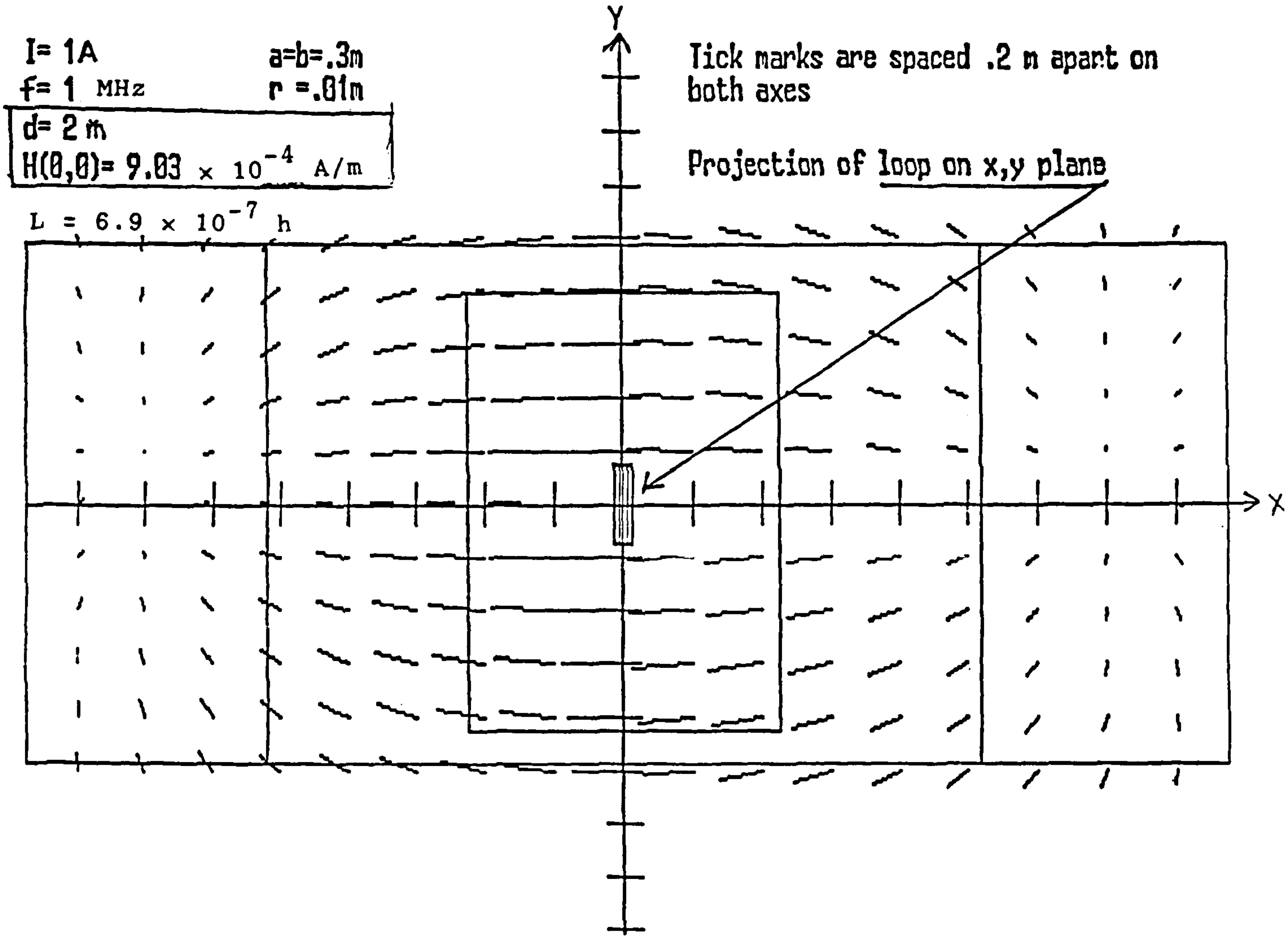

Figure 7. Magnetic field distribution in the x,y plane due to a uniform harmonic current of unit magnitude on a loop antenna with a = b = .3 m lying in the y,z plane with its center located a distance d = 2 m from the x,y plane.

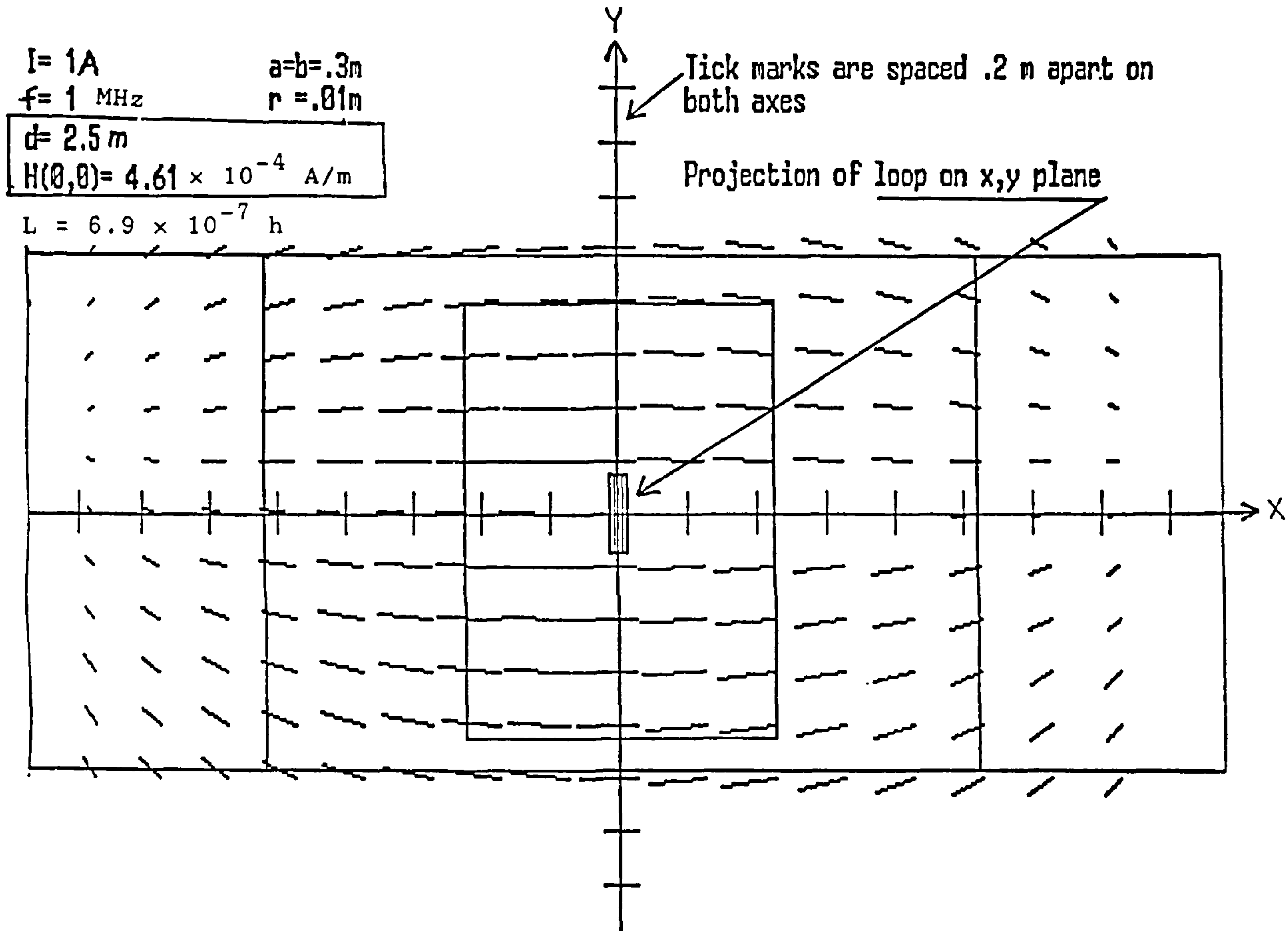

Figure 8. Magnetic field distribution in the x,y plane due to a uniform harmonic current of unit magnitude on a loop antenna with a = b = .3m lying in the y,z plane with its center located a distance d = 2.5 m from the x,y plane.

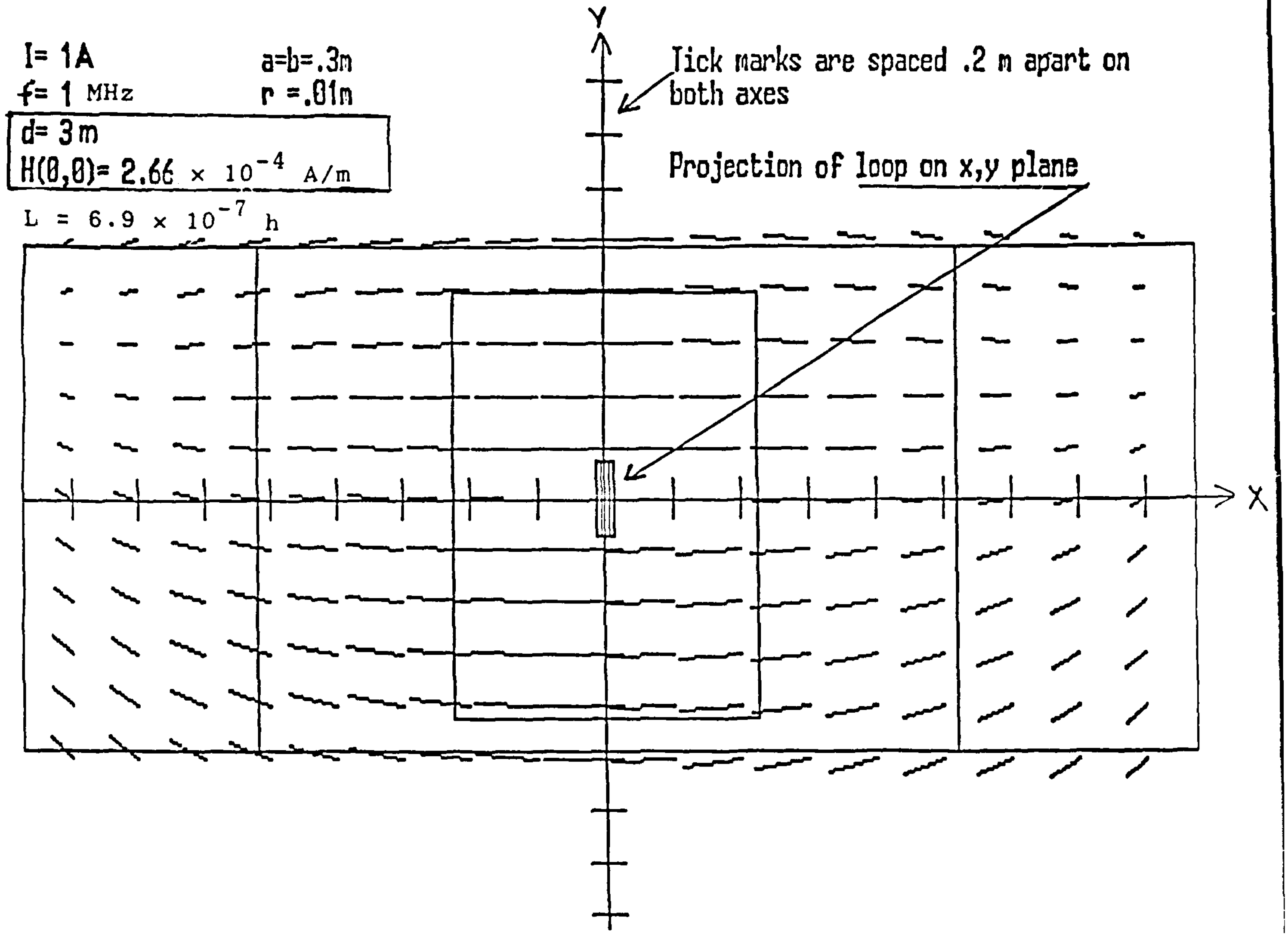

Figure 9. Magnetic field distribution in the x,y plane due to a uniform harmonic current of unit magnitude on a loop antenna with a = b = .3 m lying in the y,z plane with its center located a distance d = 3 m from the x,y plane.

the x,y plane for this arrangement, the fields at other points are always represented by lines that are less than or equal to 0.2 m in length. Thus, a field in the x direction that is uniform in magnitude over a certain area will be seen here as a series of lines spaced .2 m apart parallel to the x axis running through that area.

Figure 5 shows the field distribution in the x,y plane from a square loop 0.3 m on a side located in the y,z plane with its center on the z axis 1 m from the origin. In addition to the field distribution, the figure displays I, f, d, H(0,0), a, and b, as defined previously. Also shown are r, the radius of the loop conductor, and L, the loop inductance, where the latter is computed using the formula found in Grover.[5] In this case, a 1 A current on the loop gives $H(0,0) = 7.4 \times 10^{-3}$ A/m which means that a pulse generator producing a peak current of 1 kA = 1000 A on the loop would produce a magnetic field in the x direction with a peak of 7.4 A/m at (0,0). Unfortunately, the figure also indicates that the area over which the field can be described as uniform is less than 1 m^2. The latter is considerably smaller than an earlier estimate[1] for this setup which was

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[5] F. W. Grover, Inductance Calculations: Working Formulas and Tables, Dover Publications, NY (1962).

[1] R. L. Monroe, A Theory of Electromagnetic Shielding with Applications to MIL-STD 285, IEEE-299, and EMP Simulation, Harry Diamond Laboratories, HDL-CR-85-052-1, (February 1985).

based on calculations at an insufficent number of locations.

To improve the field distribution, it is necessary to move the loop farther from the x,y plane. This has been done in figure 6 where d has been set equal to 1.5 m without changing the other input parameters. The figure does show a significant improvement with a uniform field that covers virtually the entire area of the door (1.3 m^2). However, this improvement has been obtained at the cost of a reduction in H(0,0) from 7.4×10^{-3} to 2.2×10^{-3} A/m. Thus, for a given loop current, there is a tradeoff between the area that can be covered with a uniform field and the magnitude of that field. Figures 7, 8, and 9 show how still larger areas of uniform field can be obtained by moving the loop farther from the x,y plane. Of these, figure 8 where d = 2.5 m appears to satisfy our objective of a uniform field over an area of 4 m^2. Since a 1 A loop current gives H(0,0) = 4.6×10^{-4} A/m in this case, a peak loop current of 2.2 kA will be required to produce a simulated EMP with the desired peak field of 1 A/m.

These figures indicate that the field in the x,y plane has some of the characteristics of a magnetic dipole with virtual poles located on the x axis equidistant from the y axis. The area of uniform field lies between the poles which move farther apart as the loop moves away from the the x,y plane. The field between the poles is predominately in the x direction Thus, if the positive y axis is defined as pointing in the vertical direction, the setup described here corresponds to a vertically polarized EMP field (vertical electric field, horizontal magnetic field) incident on the side or front of the shelter. Other polarizations can be obtained simply by rotating the plane of the loop about the z axis by the appropriate number of degrees. A 90° rotation puts the plane of the loop in the x,z plane and produces a uniform magnetic field in the y direction corresponding to a horizontally polarized EMP field.

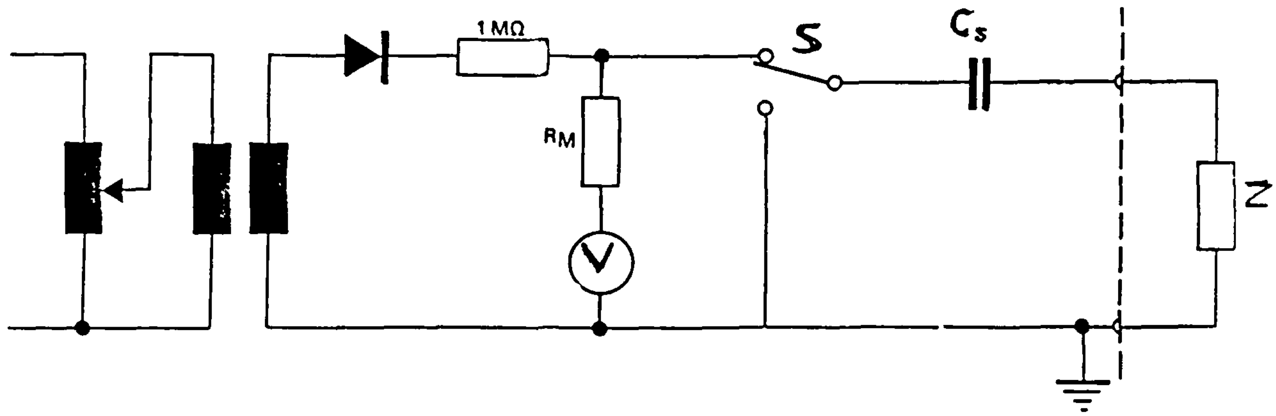
3. PULSE GENERATION IN AN INDUCTIVE LOAD

The preceding has shown that it will be necessary to generate a transient loop current with a peak of at least several thousand amps on a time scale of 10 ns in order to satisfy the simulator requirements we have specified. This must be done by driving the loop with a high-voltage pulse generator such as the one described schematically in figure 10 (a). The basic operation of these devices is well known and will not be discussed here beyond noting that the process is initiated by charging capacitor C_s to a voltage V using the rectifier circuit to the left of the switch S. When C_s is fully charged, S is thrown to its lower position, discharging C_s to ground and generating a current pulse in the load impedance Z. An equivalent circuit giving an approximate (linear) description of the current pulse is shown in figure 10 (b) where V is considered to be applied instantaneously at t = 0 on the input terminals. In this circuit, R_i and L_i refer to the internal resistance and inductance of the pulser, and R_e and L_e refer to the external resistance and inductance of the load. These can be lumped together by defining the total resistance and inductance of the circuit as follows:

$$\begin{aligned} R_t &= R_i + R_e \\ L_t &= L_i + L_e \end{aligned} \tag{3.1}$$

For a purely inductive load like the small loop, we can expect R_i >> R_e and L_e >> L_i so that (3.1) can be rewritten

(a)



(b)

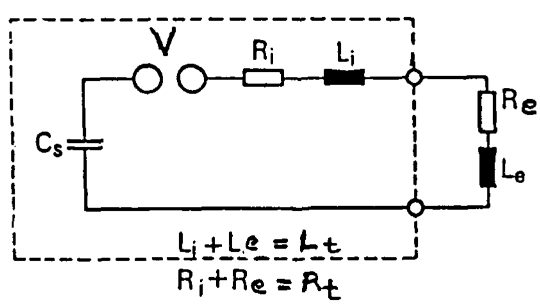


Figure 10. Schematic (a) and equivalent circuit (b) of a pulse generator.

$$R_t = R_i \equiv R$$
$$L_t = L_e \equiv L \tag{3.2}$$

where R is resistance of the pulser and L is inductance of the loop. Solving the circuit for the current gives

$$I(j\omega) = \frac{V}{j\omega\ [R + j\omega L + 1/j\omega C_s]} \quad . \tag{3.3}$$

The latter is easily transformed to the time domain,[6] giving:

<u>For D > 0</u>

$$I(t) = I_1 \exp(-C_1 t/2) \sinh(D^{1/2} t) \tag{3.4}$$

<u>For D < 0</u>

$$I(t) = I_2 \exp(-C_1 t/2) \sin[(-D)^{1/2} t] \tag{3.5}$$

where

$$I_1 = V/[LD^{1/2}] \tag{3.6}$$

$$I_2 = V/[L(-D)^{1/2}] \tag{3.7}$$

$$D = (C_1/2)^2 - C_o \tag{3.8}$$

$$C_o = 1/(LC_s) \tag{3.9}$$

$$C_1 = R/L \ . \tag{3.10}$$

Thus I(t) will have either an exponential or a damped sinusoidal waveform depending on whether C_s, R, and L are such that D is greater than or less than zero. Since the HEMP waveform is itself of the

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[6] G. Doetsch, <u>Guide to the Application of Laplace Transforms</u>, D. Van Nostrand Company LTD, London, (1961).

exponential type, our interest here will be limited to the former case, and we will attempt to choose the circuit parameters so that $I(t)$ approximates the curve in figure 2. In doing this, we will have great freedom in choosing the internal parameters C_s and R. Both of these parameters can be varied over several orders of magnitude if necessary. However, our choice of L is much more limited. We can always increase L by adding a series inductor or using multiturn loops. However, this is not a useful option, since it would increase the circuit impedance and decrease the current. We can decrease L by decreasing the size of the loop while increasing the diameter of the loop conductor. However, size reductions in high-voltage systems are limited by electrical breakdown, and it appears unlikely that an inductance much below the value for the 0.3 m square loop, $L = 6.9 \times 10^{-7}$h = 0.69 μh could be realized in a practical simulator. Accordingly, we will set the simulator specifications using $L = 0.69\ \mu$h as the target inductance for the system.

4. SPECIFICATIONS FOR A HEMP SIMULATOR

Since the HEMP waveform in figure 2 can be expressed analytically as the difference between two decaying exponentials,[4]

$$H = H_o[\exp(-\alpha_1 t) - \exp(-\alpha_2 t)] \quad A/m \tag{4.1}$$

where

$$H_o = 5.25 \times 10^4/377 = 139 \text{ A/m} \tag{4.2}$$

$$\alpha_1 = 4 \times 10^6 \text{ s}^{-1} \tag{4.3}$$

$$\alpha_2 = 4.76 \times 10^8 \text{ s}^{-1}, \tag{4.4}$$

it is useful to write equation (3.4) in the same form:

$$\begin{aligned} I(t) &= I_1 \exp(-C_1 t/2)\sinh(D^{1/2}t) \\ &= I_1 \exp(-C_1 t/2)[\exp(D^{1/2}t) - \exp(-D^{1/2}t)]/2 \\ &= (I_1/2)\left[\exp[-(C_1/2-D^{1/2})t] - \exp[-(C_1/2+D^{1/2})t]\right] . \end{aligned} \tag{4.5}$$

We can then compare (4.1) and (4.5) and note that these expressions will describe the same waveform provided

$$\begin{aligned} \alpha_1 &= C_1/2 - D^{1/2} \\ \alpha_2 &= C_1/2 + D^{1/2} \end{aligned} \tag{4.6}$$

where D and C_1 are given by (3.8) and (3.10). Since L, α_1, and α_2 are fixed, (4.6) can be regarded as a set of two equations determining C_s and R. If (4.6) is solved for C_s and R, then these parameters will specify a pulser capable of generating a current on the loop

[4] Bell Laboratories, EMP Engineering and Design Principles, Whippany NJ (1975).

that reproduces the HEMP waveshape. Since (4.6) is nonlinear in R and C_s, we must resort to successive approximations to obtain a solution. Using an initial estimate of $R = 300\ \Omega$ and $C_s = .5$ nf, we obtain

$$R = 331\ \Omega\ , \qquad C_s = 0.755 \text{ nf}\ . \tag{4.7}$$

The reader can verify that (4.7) satisfies (4.6) to an accuracy of better than 1 %.

Figure 11 is a plot of I(t) computed with (3.4) for a pulse generator specified by

$$\begin{aligned} &\underline{V = 2 \times 10^6 \text{ V} = 2 \text{ MV}} \\ &\underline{R = 331\ \Omega} \\ &\underline{C_s = .755 \text{ nf}} \end{aligned} \tag{4.8}$$

driving an inductive load equal to that of a 0.3 m square loop where

$$\underline{L = 0.69\ \mu h}\ . \tag{4.9}$$

It shows a peak current of 5.8 kA and a waveform identical to the HEMP field in figure 2. This pulser driving the 0.3 m square loop would generate a spatially uniform magnetic field with the HEMP waveform and a peak field of 2.7 A/m over an area of 4 m^2 on a plane surface located 2.5 m from the center of the loop (fig. 8). Thus, it would satisfy the requirements for the EMP simulator specified at the outset.

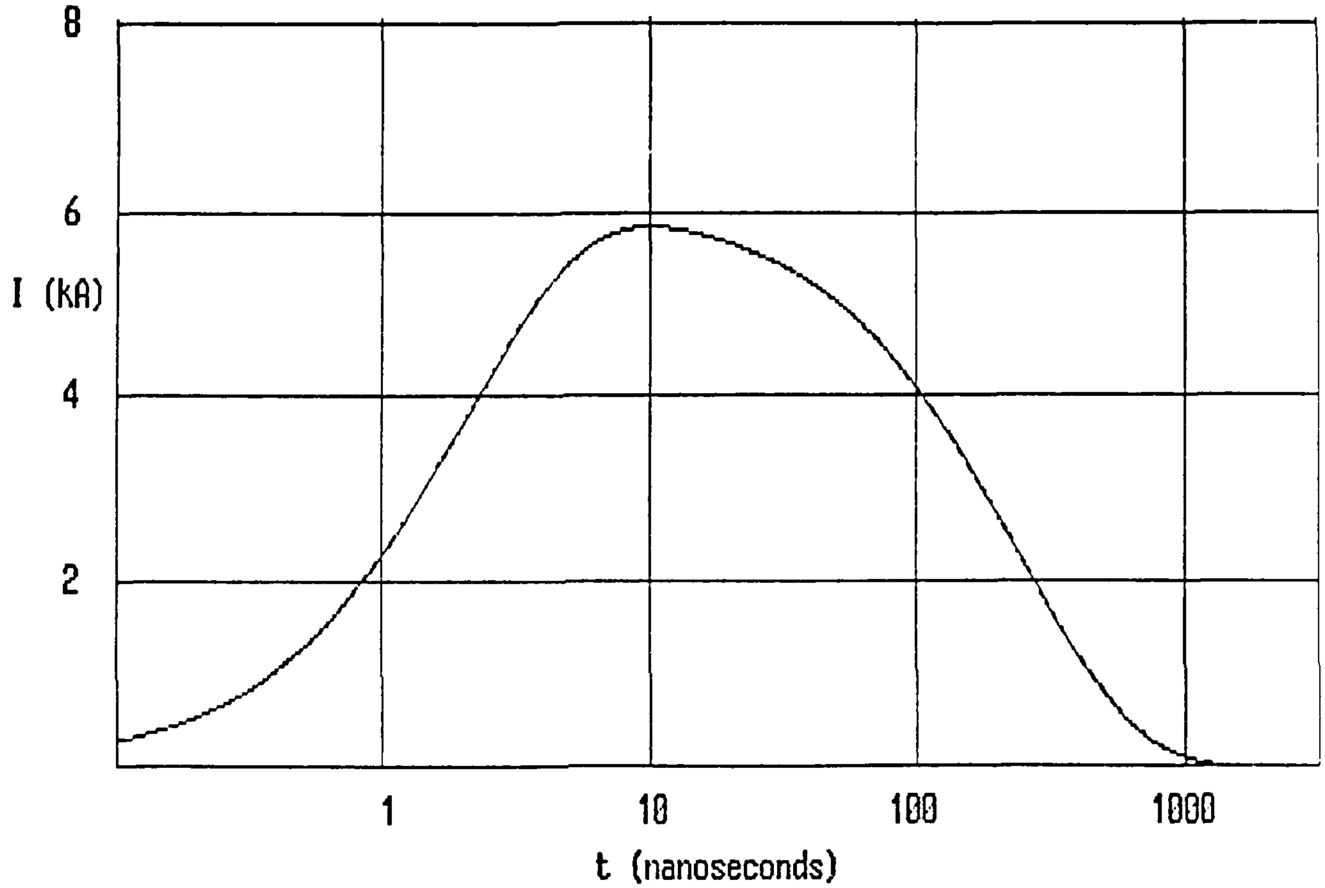

Figure 11. Load current I produced by a 2 MV pulse generator where C_s = .755 pf, R = 331 Ω, and L = .69 μh.

5. CONCLUSIONS

The simulator we have specified would allow one to determine the overall efficiency of an enclosure as a shield against HEMP fields by a piece-wise process in which 4 m^2 sections of the enclosure are exposed in succession to magnetic fields with a HEMP-like structure, polarization, and waveform. The peak external field of 2.7 A/m should produce a dynamic range of at least 65 dB for shielding measurements since an internal field of 1×10^{-3} A/m = 1 mA/m can usually be measured. If greater dynamic range is needed, one can obtain this at the cost of a reduced area of coverage by moving the loop closer to the enclosure. For example, by moving the center of the loop from d = 2.5 m to d = 1.5 m (fig. 6), the peak field is increased by a factor of 4.7 to 12.7 A/m. which translates to a dynamic range of more than 80 dB. The shielding effectiveness of the vast majority of shelters will be found to fall within this range.

Finally, we note that it may be useful to simulate HEMP fields with waveforms differing from the waveform shown in figure 2 since the latter is only an average. This can be done easily by adjusting C_s and R. However there are limitations on what can be achieved in this way. Figures 12, 13, and 14 show the types of waveforms that can be obtained by letting C_s range from 0.1 to 10 nf and R from 200 to 1600 Ω. In general, these figures show that smaller R and larger C_s produces larger peak currents occurring at later times while larger R and smaller C_s produces smaller peaks at earlier times compared to figure 11. Thus, an earlier (< 10 ns) peak can be obtained by sacrificing magnitude, and a larger magnitude can be obtained by accepting a later (> 10 ns) peak, but a peak that is both larger and earlier than the one in figure 11 is not possible unless L can be significantly reduced.

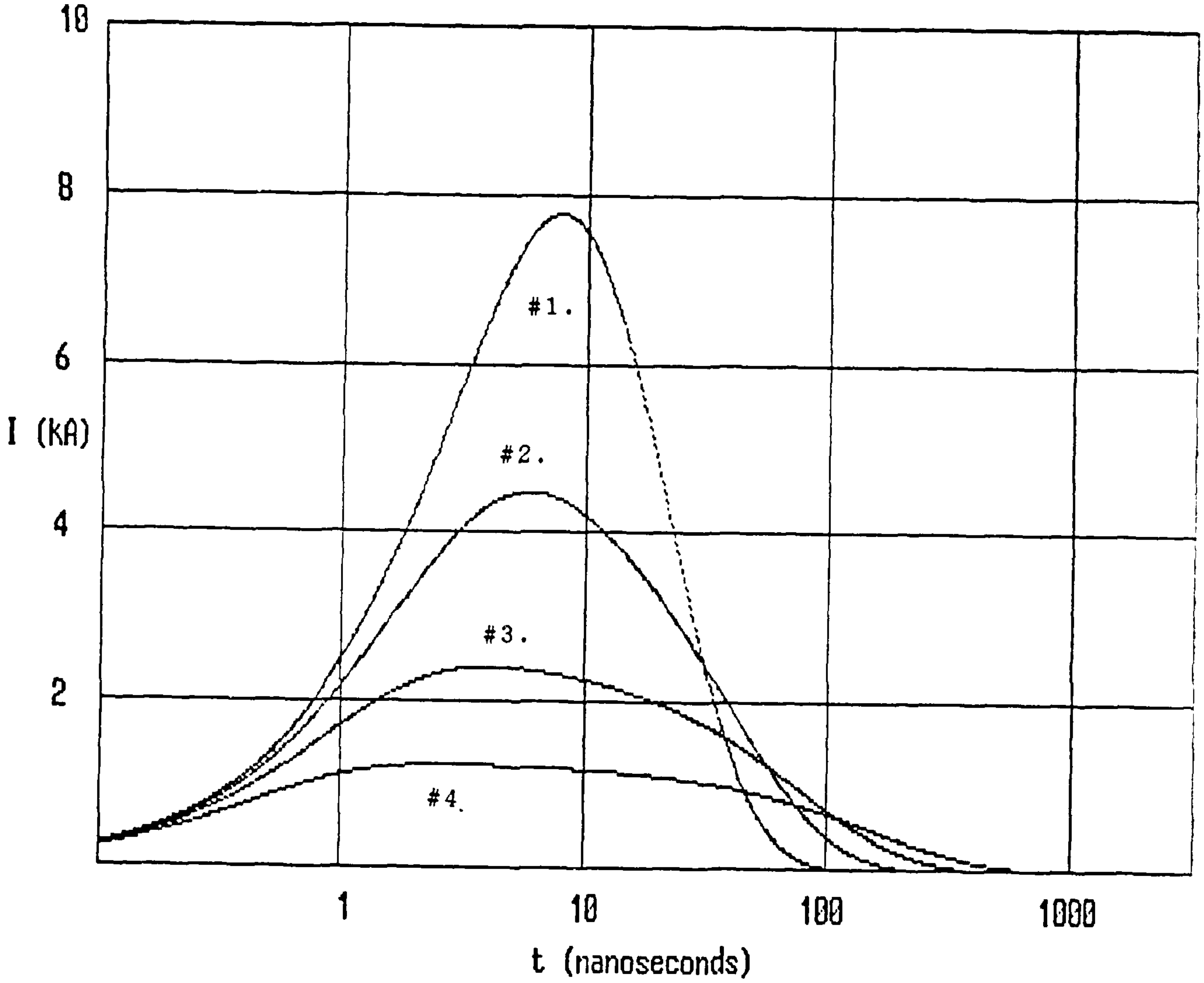

Figure 12. Load currents I produced by a 2 MV pulse generator where $L = .69\ \mu h$, $C_s = .1\ nf$, and:

#1. R = 200 Ω

#2. R = 400 Ω

#3. R = 800 Ω

#4 R = 1600 Ω

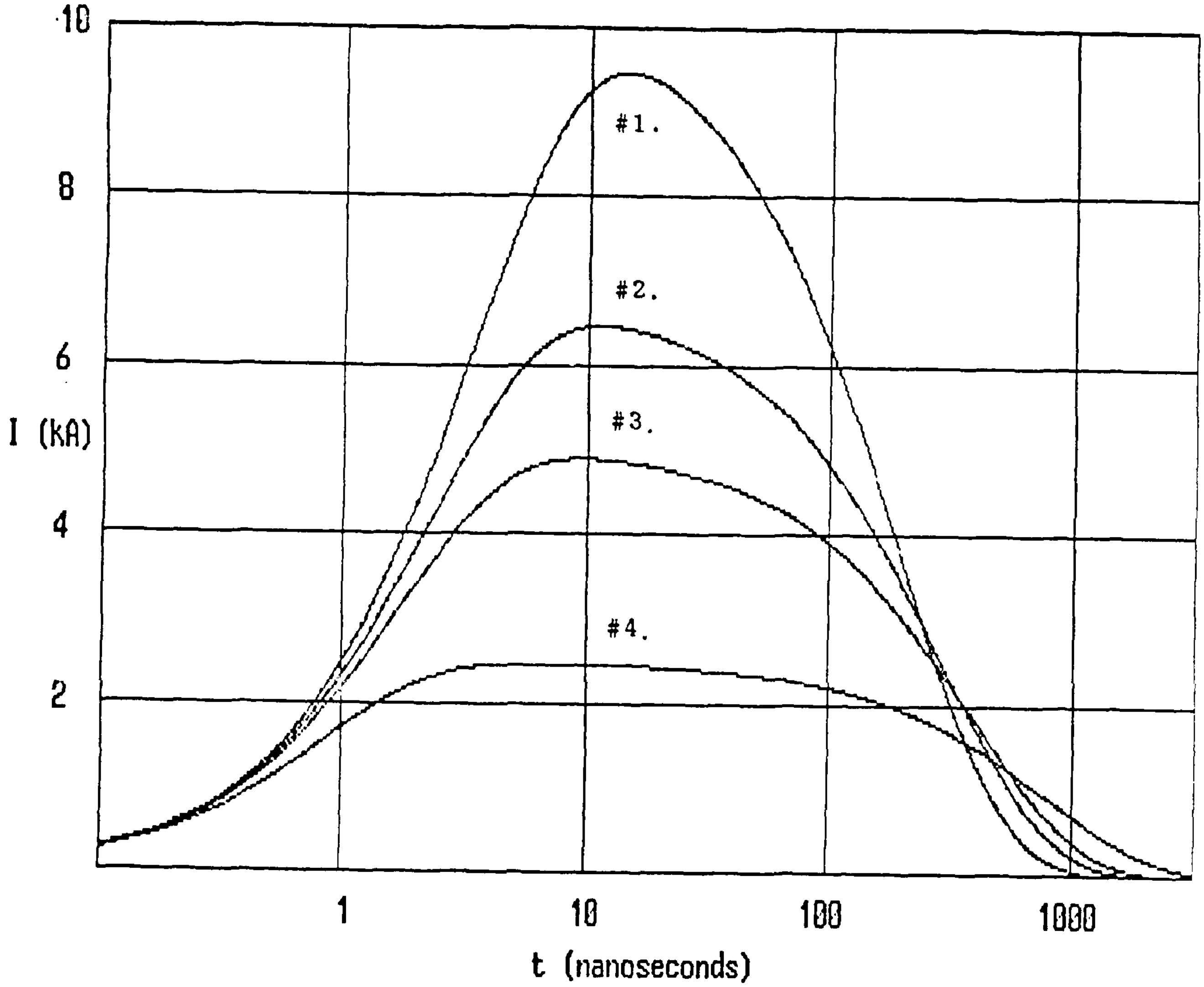

Figure 13. Load currents I produced by a 2 MV pulse generator where L = .69 μh, C_s = 1 nf, and

#1. R = 200 Ω

#2 R = 300 Ω

#3 R = 400 Ω

#4 R = 800 Ω

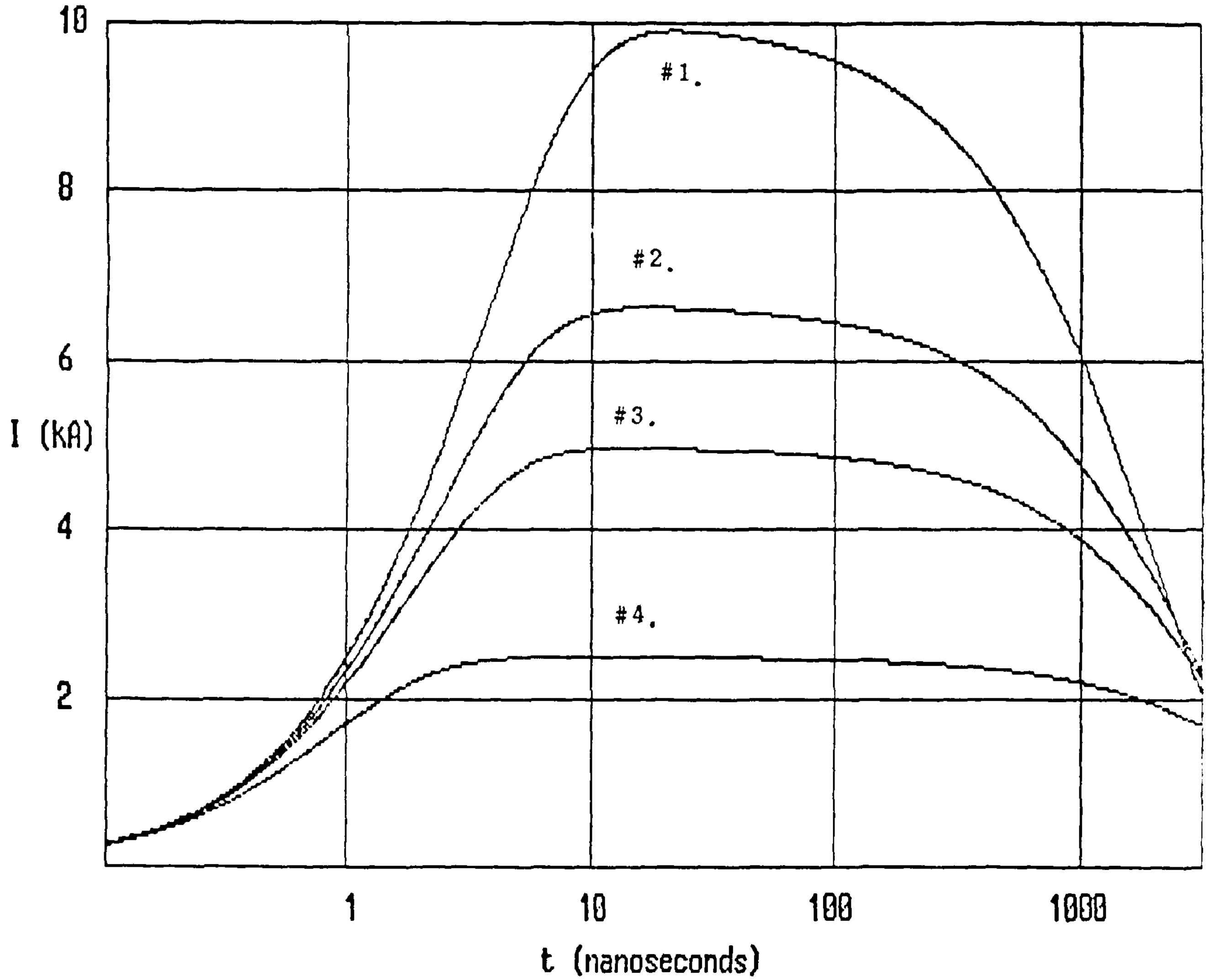

Figure 14. Load currents I produced by a 2 MV pulse generator where L = .69 μh, C_s = 10 nf, and

#1 R = 200 Ω

#2 R = 300 Ω

#3 R = 400 Ω

#4 R = 800 Ω

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